RESEARCH ARTICLE OPEN ACCESS

DC MOTOR CONTROL USING FIRST-ORDER COMPENSATOR AND PD-PI CONTROLLER COMPARED WITH A PI CONTROLLER

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Abstract:

This paper investigates the optimal control of an armature-controlled DC motor through the use of a compensator from the second generation of control compensators and a controller from the second generation of PID controllers. The proposed compensator is an I-first order compensator and the proposed controller is a PD-PI controller. The compensator and controller are tuned for good control system performance in tracking a specific desired motor speed. The performance of the control system with the proposed compensators is compared with PI controller from the first generation of PID controllers to control the same motor-speed process. The DC motor speed is identified as a controlled process experimentally for two possible transfer function models. The characteristics of the step time responses are compared with those of the conventional PI controller. The best compensator/controller for the control of the DC motor is assigned and compared with other controllers available in the literature.

***Keywords* — DC motor control, I-first order compensator, PD-PI controller, PI controller, compensator/controller tuning.**

I. INTRODUCTION

DC motors have outstanding advantages such as: high starting torque, easy control of its speed, not having harmonic effect (causing noise, warming and rotor harmonic current), prompt control, low-cost operation and easy speed regulation using a potentiometer [1]. Because of those advantages over AC motors, it is in wide use in too many applications such as: automotive industries, cranes, industrial tools, air compressors, elevators, electric tractions and home products [2]. Here are some of the research efforts in presenting some aspects related to modeling and control of DC motors since 2007:

Amer, Salem and Atia (2007) presented an adaptive single neuro control for a separately excited DC motor. They modeled the motor and simulated its step time response with experimental verification with good agreement with the simulated results [3]. Maheswararao, Bebu and Amaresh (2011) presented a sliding mode controller to control the speed of a separately excited DC motor. The controller structure aimed at reducing the maximum overshoot, the steady-state error and the settling time. They used a PI controller to first control the motor, develop the motor's model, then used a slide-mode controller to control the motor. They compared with a PI controller showing the superiority of the sliding-mode control over the PI control [4]. Sahir and Khan (2014) outlined that in DC motor-based servo systems and speed control applications, the PID controller is usually used due to its ease of implementation, ruggedness and easy tuning. They explored some metaheuristic algorithms for PID controller design and conducted comparison with classical tuning techniques [5].

Abut (2016) used linear quadratic performance (LQP) and PID methods for the optimal control of a DC motor speed process. He applied process and computational noise to the DC motor system and designed a Kalman filter to increase the controller performance in the noise environment. His MATLAB simulation results were in favor of the LQR method [6]. Al-Bargothi, Qaryouti and Jaber (2019) implemented an adaptive mechanism to utilize a recursive least squares (RLS) algorithm with rate limits to tune PID controller gains for adaptive PID controller. They outlined that their adaptive PID controller enhanced both transient and steady-state speed responses [7].

Cojuhari et al. (2022) proposed an approach to synthesize the PID control algorithm for speed control of the DC motor based on the maximum stability degree method with iterations. They identified the controlled motor analytically and experimentally and presented case studies for the

DC motor control based on the parametric optimization and internal control methods [8]. Li (2024) evaluated the effectiveness of PD control in maintaining desired speed outputs with its robustness against disturbances. He handled how to get a fast time response without steady-state error and provided insights for designing reliable control systems in some industrial applications [9]. Larrode and Jarreta (2025) outlined that adopting fractional-order controllers in cascade schemes did not guarantee better performance and paired fractional exponents for inner and outer PI controllers can worsen the DC motor's behaviour. They analysed key functions such as overshoot, rise time and peak current during speed and current changes. They employed Oustaloup's recursive approximation to model fractional-order elements with MATLAB simulations [10].

II. THE DC MOTOR SPEED AS A PROCESS

Any control strategy for the control of the DC motor speed depends on its dynamic transfer function model which has to be identified first before the proposal of any control strategy. Therefore, a laboratory test rig was designed, assembled and tested in the Automatic Control Laboratory of the Mechanical Design and production Department of the Faculty of Engineering, Cairo University. The test rig is shown in Fig.1.

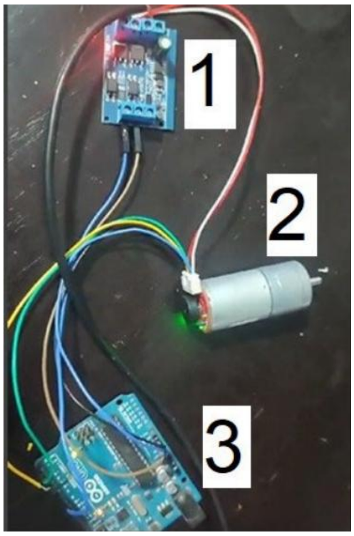

Fig.1 Test rig for DC motor speed modeling and control.

It is composed of three elements:

1. Motor-drive with pulse width modulation Type MOSFET Trigger Switch Driver Module, 4V~60V, 10A, 600W.
2. 130 rev/min, 12 V, armature-controlled DC motor Type GA25-370 with encoder and gearbox.
3. Arduino Uno Rev3 With CH340 Uploader.

The Arduino card acts as an interface between the motor and the PC receiving the measured speed signal and forwarding the control signal to the motor through its drive.

To avoid any source of nonlinearity in the differential model of the DC motor, we are going to rely upon experimental identification by supplying a 12 V step input to the motor drive and recording the motor-speed time response in a IDE software environment. The result of this step is shown in Fig.2.

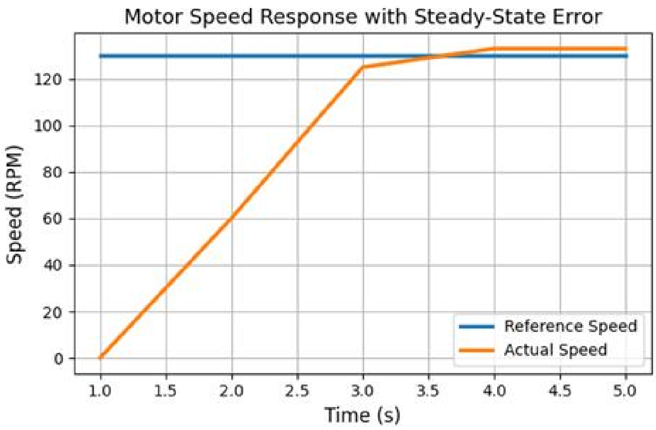

Fig.2 Experimental step time response of the DC motor.

The DC motor speed is identified as follows:

1. The data in Fig.2 is digitized in the time range $0 \leq t \leq 4.5$ s.
2. A MATLAB code was written to minimize an ITAE error criterion (performance index) [11] to identify the proposed model parameters of the DC motor using the MATLAB optimization toolbox [12].
3. First of all an 0/2 transfer function was proposed as expected from the analytical modeling of an armature-controlled DC motor [13]. It is fitted to the data in step 2 with 0.9385 correlation coefficient.
4. From our experience in process modelling we have felt that it is in need to another

simple zero added to its two simple poles. We added a simple zero to be a 1/2 transfer function model and run the identification code to have the parameters of the new model with 0.9880 correlation coefficient which is much better that he first one. The transfer function model of the identified DC motor, $G_p(s)$ is given by:

$$G_p(s) = (b_0 s+b_1)/(s^2+a_1 s+a_2) \quad (1)$$

Where:

$$b_0 = 5.0009 \quad , \quad b_1 = 2085.69$$
$$a_1 = 2197.91 \quad , \quad a_2 = 1543.045 \quad (2)$$

5. Eq.2 depicts a numerical fact which is the small value of b_0 relative to b_1 which means that it may be neglected with respect to b_1 reducing Eq.1 to:

$$G_p(s) = b_1/(s^2+a_1 s+a_2) \quad (3)$$

6. Eq.6 requires verification. The step time response of the DC motor for both models and the experimental step time response are drawn using the '*ide software*' (specialized for Arduino microcontroller) [14] and shown in Fig.3.

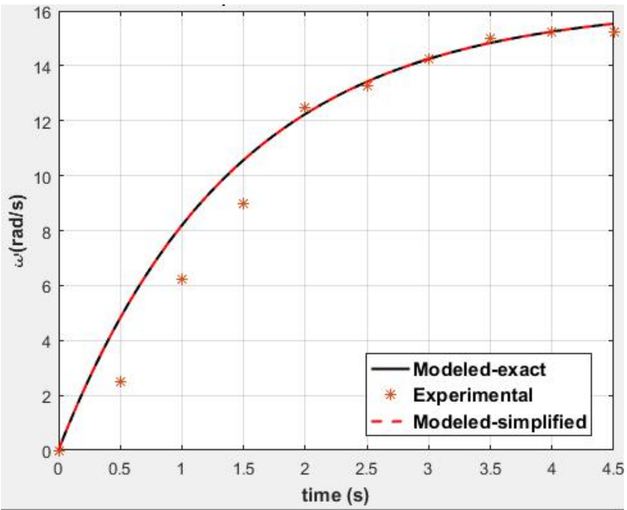

Fig.3 Step time response of the DC motor speed as a process.

COMMENTS:

- Using the 1/2 transfer function model of Eq.1 gives the same step time response of the DC motor speed as the simplified 0/2 transfer function model in Eq.3.
- The simplified model is approved and it will be used in the analysis of the proposed controllers/compensators to control its speed.

III. DC MOTOR SPEED CONTROL USING A PI CONTROLLER

- As a reference for control system characteristic comparison, a conventional PI controller from the first-generation of PID controllers is proposed to control the DC motor speed.
- The PI controller is still proposed to control the DC motor speed [15], [16], [17].
- It has only two gain parameters: proportional gain K_{pc1} and integral gain K_{i1}. We tuned the PI controller for the DC motor having the transfer function model of Eq.3 using an ITAE performance index [11] and the MATLAB optimization toolbox [12]. The tuned controller parameters are given by:

$$K_{pc1} = 17.99647 \, , K_{i1} = 11.62101 \quad (4)$$

- The step time response for the DC motor-controlled speed using the simplified process in Eq.3 and the tuned PI controller is shown in Fig.4 for a desired motor speed of 130 rev/min.

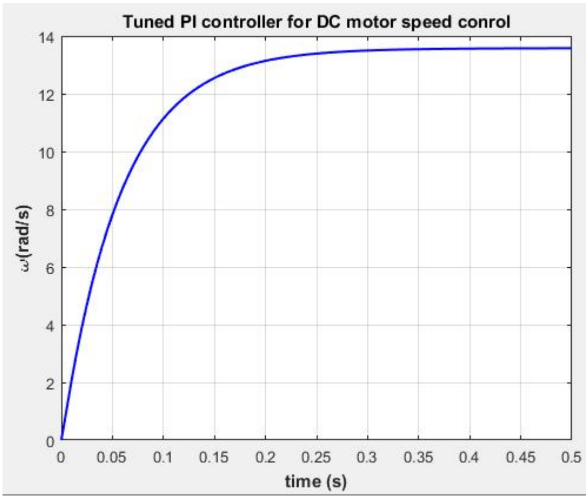

Fig.4 Step time response of the PI controlled DC motor.

COMMENTS:

- Maximum overshoot: zero
- Settling time with ± 2 % tolerance: 0.236 s
- Rise time: 0.1288 s

- Steady-state error: zero

IV. DC MOTOR SPEED CONTROL USING AN I-FIRST ORDER COMPENSATOR

The I- first order compensator is one of the second generation compensators presented by Professor Galal Hassaan (the first author of the present paper) since 2014 [18]-[20]. The I- first order compensator has a transfer function $G_{I1st}(s)$ given by [18]:

$$G_{I1st}(s) = \left(\frac{K_{i2}}{s}\right)[(s+z_2)/(s+p_2)] \quad (5)$$

The I-first order compensator has three parameters to be tuned: K_{i2}, z_2 and p_2. They are tuned as follows:

- The simplified transfer function of the process in Eq.3 is factorized in terms of simple poles as follows:

$$G_p(s) = b_1/[(s+a_{11})(s+a_{21})] \quad (6)$$

Where:

$$a_{11} = 0.70227\,,\, a_{21} = 2197.93 \quad (7)$$

- The open-loop transfer function of the closed-loop control system of the DC motor $[G_{I1st}(s)G_p(s)]$ is obtained using Eqs.5 and 6.
- The zero/pole cancellation technique [21] is used to cancel the compensator zero with the process pole s+0.70227 giving the compensator zero as:

$$z_2 = 0.70227 \quad (8)$$

- The closed-loop transfer function, $M_2(s) = G_{I1st}(s)G_p(s)/[1+ G_{I1st}(s)G_p(s)]$ for a unit feedback control system reveals a 0/3 orders third-order dynamic system in the compensator parameters K_{c2} and p_2.
- An ITAE performance index [11] function of the error between the desired DC motor speed and the simulated motor speed is minimized using the MATLAB optimization toolbox [12] providing the remaining compensator parameters as:

$$K_{i2} = 1.2291x10^6\ ,\ p_2 = 12560.847 \quad (9)$$

- The step time response of the control system incorporating the I-first order compensator and the DC motor speed process is drawn using the step command of MATLAB [22] as shown in Fig.5.

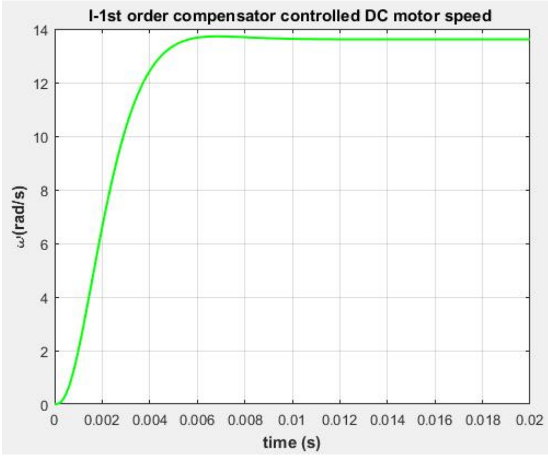

Fig.5 DC motor speed control using an I-first-order compensator.

COMMENTS:

- Maximum overshoot: 0.759 %
- Settling time with ± 2 % tolerance: 0.0049 s (compared with 0.236 s for the PI controller).
- Rise time: 0.003 s (compared with 0.1288 s for the PI controller).
- Steady-state error: zero

V. DC MOTOR SPEED CONTROL USING A PD-PI CONTROLLER

- The PD-PI controller is one of the second generation of PID controllers introduced by Prof. Galal Hassaan since 2014 to control processes having bad dynamics such as: highly oscillating second-order process [23], integrating plus time-delay process [24], BLDC motor [25], blending process [26], greenhouse humidity process [27], liquefied natural gas tank level process [28] and human blood urine nitrogen [29]. It has the transfer function $G_{c2}(s)$ given by [25]:

$$G_{c3}(s) = (K_{pc3} + K_{d3}s)(K_{pc4} + K_{i4}/s) \quad (10)$$

Where:

K_{pc3} = proportional gain of the PD control.
K_{d3} = derivative gain of the PD control.
K_{pc4} = proportional gain of the PI control.
K_{i4} = integral gain of the PI control.

- The PD and PI control modes of the PD-PI controller are set in cascade after the error detector of the single closed-loop block diagram of the proposed control system for the DC motor speed.
- The four parameters of the PD-PI controller are tuned as follows:
- The transfer function of the PD-PI controller in Eq.10 is rewritten in the form of simple poles of the controlled process (Eq.6) as follows:

$$G_{c3}(s) = \left(\frac{K_{d3}K_{pc4}}{s}\right)\left[s + \left(\frac{K_{pc3}}{K_{d3}}\right)\right][s + \left(\frac{K_{i4}}{K_{pc4}}\right)] \quad (11)$$

- The PD-PI controller has two simple zeros as depicted in Eq.11 and the DC motor speed has 2 simple poles as depicted by Eq.6.
- The zero/pole cancellation technique [21] is applied to the open-loop transfer function of the block diagram loop for the motor speed control. The first controller zero (in Eq.11) is chosen to cancel the simple pole ($s+a_{11}$) of the DC motor speed process in Eq.6 providing the following relationship between the PD control parameters as:

$$K_{d3} = K_{pc3}/a_{11} \quad (12)$$

- The second zero of the PD-PI controller in Eq.11 is cancelled with the second pole of the process in Eq.6 providing the following relationship between the PI control parameters as:

$$K_{i4} = a_{21}K_{pc4} \quad (13)$$

- The transfer function of the closed-loop control system, $M_3(s)$ is deduced using Eqs.6 and 11 in a unit feedback single loop control system and after the application of the zero/pole cancellation technique producing Eqs.12 and 13. The result is as follows:

$$M_3(s) = 1 / (T_3 s + 1) \quad (14)$$

Where: T_3 is the time constant of the resulting transfer function of the closed-loop control system given by:

$$T_3 = \frac{1}{b_1 K_{d3} K_{pc4}} \quad (15)$$

- Eq14 depicts a first-order control system having a settling time to ± 2% tolerance, T_s related to its time constant T_3 through the relationship [31]:

$$T_s = 3.9118\, T_3 \quad (16)$$

- Eq.16 helps the control system designer to set any desired settling time and then assign the required DC motor speed time constant accordingly.
- Let us assume a desired settling time of 0.004 s (4 ms). Eq.16 gives T_3 as:

$$T_3 = 0.00102\, s \quad (17)$$

- Now, to be able to use Eq.12, we assume the proportional gain K_{pc3} to have a unit value and use Eq.12 to give the derivative gain K_{d3} as:

$$K_{d3} = 1.42395 \quad (18)$$

- With K_{d3} and T_3 identified, Eq.15 gives the proportional gain K_{pc4} as:

$$K_{pc4} = 0.32928 \quad (19)$$

- Finally, Eqs.13 and 19 are combined to provide the integral gain K_{i4} as:

$$K_{i4} = 723.744 \quad (20)$$

- The transfer function in Eq.14 and the tuned controller gain parameters produce the step time response of the DC motor speed for a desired speed of 130 rev/min and shown in Fig.6 as generated by the MATLAB 'step' command [22].

COMMENTS:

- Maximum overshoot: zero
- Settling time with ± 2 % tolerance: 0.004 s (compared with 0.236 s for the PI controller).
- Rise time: 0.00224 s (compared with 0.1288 s for the PI controller).
- Steady-state error: zero

VI. COMPARISON OF THE TIME-BASED CHARACTERISTICS

Graphical Comparison:

- The time-based characteristics of the control systems incorporating the controller /compensators proposed to control the DC motor speed are compared graphically through the step time response as depicted in Fig.7.

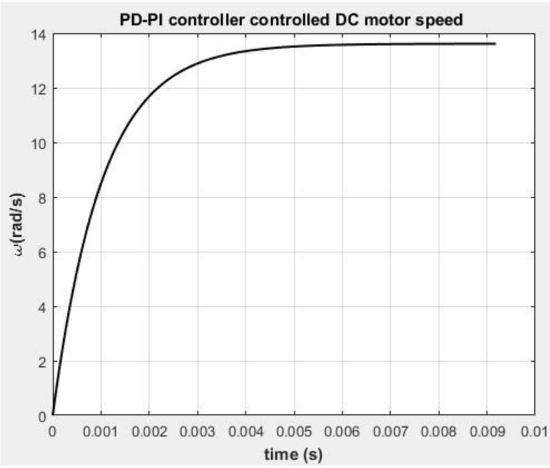

Fig.6 DC motor speed control using a PD-PI controller.

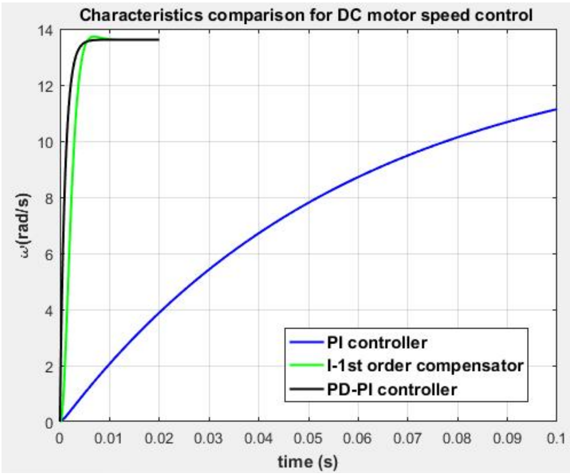

Fig.7 Graphical characteristic comparison of DC motor speed control.

Numerical Comparison:

- Numerical comparison for the time-based characteristics of the step time response for reference input tracking of the control system with the proposed controllers/compensator is presented in Table 1 with comparison with the application of a conventional PI controller used to control the same DC motor.

TABLE 1
TIME-BASED CHARACTERISTICS COMPARISON FOR THE CONTROLLED DC MOTOR SPEED

Controller/ compensator	PI controller	I-first order compensator	PD-PI controller
OS_{max} (%)	0	0.759	0
T_s (s)	0.236	0.0049	0.004
T_r(s)	0.1228	0.003	0.0022
e_{ss} (rad/s)	0	0	0

OS_{max}: Maximum percentage overshoot.
T_s: Settling time to ±2 % tolerance.
T_r: Rise time.
e_{ss}: steady-state error.

- To explore the success of the proposed best compensator/controller to control the speed of the DC motor, some of its time-based characteristics are compared with those of some other controllers as presented in Table 2.

TABLE 2
CHARACTERISTIC COMPARISON WITH OTHER CONTROLLERS

Controller	T_s(s)	OS_{max} (%)	e_{ss} (rad/s)	Reference Number
Neoro	1.8	4.28	0	3
Adaptive PID	0.117	0.205	0.049	7
Fractional-order PI	1.0015	8.33	0	10
PD-PI	0.004	0	0	present

VII. CONCLUSIONS

- The research work presented in this research paper handled the control of an armature-controlled DC motor for the best performance for reference input tracking.
- An I-first order compensator from the second generation of control compensators and a PD-PI controller from the second generator of PID controllers were proposed to control the DC motor compared with a PI controller from the first generation of PID controllers.
- The motor was identified experimentally to avoid the effect of nonlinearity and noise. Its transfer function model was reduced from 1/2 to 0/2 orders with reasonable justifications.
- The proposed compensators were tuned using multiple approaches based on applying the zero/pole cancellation, MATLAB optimization toolbox and fulfilling specific settling time.
- The PI controller was tuned by the authors using MATLAB optimization toolbox.
- The purpose of the investigated controllers/compensator was to track a

specific reference input of 130 rev/min (13.6135 rad/s).

- The proposed PD-PI succeeded to eliminate completely the maximum percentage overshoot of the DC motor.
- The proposed compensator/controller succeeded to reduce the settling time of the control system (with respect to the 2 % tolerance) to values in the range: $0.004 \leq T_s \leq 0.0049$ s compared with 0.236 s for the PI controller.
- The proposed compensators succeeded to reduce the rise time to $0.0022 \leq T_r \leq 0.003$ s compared with 0.1288 s for the PI controller.
- The best controller/compensator was chosen to be the PD-PI controller based on its time-based characteristics in Table 1 compared with the other compensator/controllers.
- The PD-PI controller could compete with three other controllers: Neoro controller, Adaptive PID controller and fractional-order PI controller when controlling a DC motor speed.

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DEDICATION

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- Emeritus Professor of Mechanical Engineering.
- Father of Egyptian hydraulic control systems.
- Ph. D. from Claude Bernard University, Lyon, France.
- Author of '*Fluid Power Engineering'*, McGraw Hill, 2009, 2012.
- Vice Dean of the Modern Academy for Engineering and Technology, Cairo (2016-now).
- One of the famous staff members of the Military Technical College from 1980 to 2005.
- Lectured: Fluid mechanics, automatic control, aircraft hydraulic and pneumatic systems, missile hydraulic and pneumatic systems, hydraulic and electro-hydraulic servo-systems.
- He conducted research with a lot of research authorities in Egypt and outside Egypt.
- He supervised 29 M. Sc. Theses and 5 Ph. D. Theses.
- He published 67 research papers after his Ph. D. in refereed conferences and research journals.
- This is why we dedicated this research work to the father of '*Egyptian fluid power control*', Prof. **Mahmoud Galal Rabie**.